Three-dimensional geometric comparison of partial and complete flexible mitral annuloplasty rings

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Background: It has previously been shown in sheep that mitral annular physiologic dynamics during the cardiac cycle are abolished by complete ring annuloplasty, but recent clinical studies suggest that flexible partial ring annuloplasty preserves normal mitral annular dynamics.

Methods: Eight radiopaque markers were sutured equidistantly around the mitral anulus in 3 groups of sheep: no-ring control animals (n = 16); animals with a flexible Tailor partial ring annuloplasty (n = 6; St Jude Medical, Inc, St Paul, Minn); and animals with a flexible Duran ring annuloplasty (n = 7; Medtronic, Inc, Minneapolis, Minn). After 7 to 10 days' recovery, 3-dimensional marker coordinates were measured by biplane cinefluoroscopy. Mitral annular area and folding (defined as displacement of the mitral anulus from a least-squares plane) and mitral annular septal-lateral and commissure-commissure dimensions were calculated from the 3-dimensional marker coordinates throughout the cardiac cycle every 17 ms.

Results: In the no-ring control group mitral annular area varied from 8.0 ± 0.2 to 7.2 ± 0.2 cm^2 (10% ± 2%), and the septal-lateral and commissure-commissure dimensions varied from 27.7 ± 0.4 to 25.9 ± 0.4 mm (7% ± 1%) and from 38.2 ± 0.8 to 36.4 ± 0.8 mm (5% ± 1%), respectively (mean ± standard error of the mean, $P < .001$ for all comparisons). In the Duran ring annuloplasty and Tailor partial ring annuloplasty groups, the anulus was fixed in size throughout the cardiac cycle (area = 4.8 ± 0.1 and 5.3 ± 0.3 cm^2, septal-lateral = 21.8 ± 0.7 and 22.0 ± 0.8 mm, and commissure-commissure = 27.7 ± 0.7 and 31.2 ± 1.7 mm). Mitral annular folding did not differ significantly between the control and Tailor partial ring annuloplasty groups but was dampened in the Duran ring annuloplasty group.

Conclusions: Partial Tailor flexible ring annuloplasty fixed mitral annular area and dimensions throughout the cardiac cycle in sheep; however, it preserved physiologic mitral annular folding dynamics, which might be important in terms of long-term valve function and prevention of left ventricular outflow tract obstruction.

Mitral valve repair is the preferred surgical treatment for patients with mitral regurgitation (MR) of degenerative cause and is considered by many surgeons to be the best surgical approach for those with ischemic MR.[1-3] Advantages of repair over replacement include preservation of left ventricular (LV) function, lower operative mortality risk, and freedom from postoperative thromboembolism, endocarditis, and anticoagulation-related hemorrhage.[4-6]

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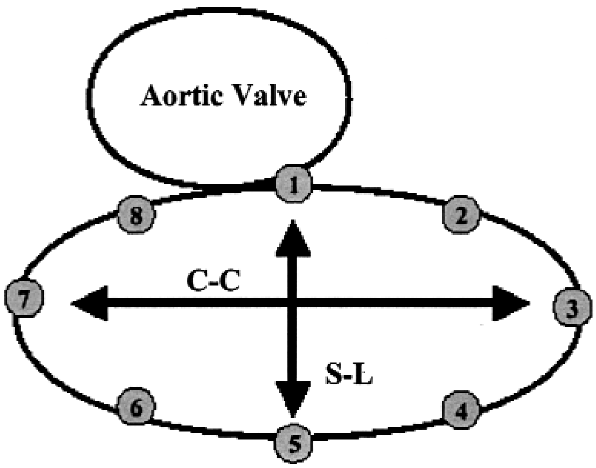

Figure 1. Miniature radiopaque markers sutured to the mitral anulus. Markers *2* and *8* were sutured to the right and left fibrous trigones, respectively. The anterior (or fibrous) anulus is defined as the anulus enclosed between the 2 fibrous trigones (ie, subtended between markers *2* and *8*). The posterior (or muscular) anulus is defined as the remaining anulus. *SL,* Septal-lateral dimension; *CC,* commissure-commissure dimension.

TABLE 1. Hemodynamics

	No Ring	Tailor	Duran	ANOVA
HR (beats/min)	100 ± 11	104 ± 9	104 ± 6	NS
EDP (mm Hg)	16 ± 6	16 ± 5	20 ± 4	NS
ESP (mm Hg)	86 ± 25	87 ± 11	90 ± 14	NS
EDV (mL)	159 ± 36	179 ± 17	172 ± 25	NS
ESV (mL)	129 ± 30	144 ± 15	145 ± 22	NS
SV (mL)	30 ± 9	35 ± 10	27 ± 8	NS
EF (%)	19 ± 4	19 ± 4	16 ± 4	NS
+dP/dtmax (mm Hg/s)	1426 ± 365	1305 ± 160	1163 ± 200	NS
–dP/dtmin (mm Hg/s)	1475 ± 475	1496 ± 165	1425 ± 284	NS

All comparisons with repeated-measures analysis of variance were not significant *(NS)* across the 3 groups. *ANOVA*, Analysis of variance; *HR*, heart rate; *EDP*, end-diastolic pressure; *ESP*, end-systolic pressure; *EDV*, end-diastolic volume; *ESV*, end-systolic volume; *SV*, stroke volume; *EF*, ejection fraction; *+dP/dtmax*, maximum positive LV +dP/dt; *–dP/dtmin*, minimum negative LV dP/dt.

Surgical strategies for mitral valve repair vary, but most techniques include annuloplasty as part of the repair, which is purported to remodel the anulus to restore its anatomic shape, to correct the annular dilatation, and to provide a supportive scaffold that stabilizes the valve repair. Use of annular rings, pioneered by Carpentier and colleagues[7] and Duran and Umbago,[8] has become the most common approach for mitral annuloplasty and is associated with consistent outcomes. Three general types of rings are used: (1) a complete rigid or semirigid ring, such as the Carpentier-Edwards Classic or Physio rings[7] (Baxter Healthcare Corp, Santa Ana, Calif); (2) a complete flexible ring, such as the Duran ring[8] (Medtronic, Inc, Minneapolis, Minn); and (3) a partial (posterior) flexible ring, such as the Cosgrove-Edwards ring[9] (Baxter) or the St Jude Medical Tailor ring (St Jude Medical, Inc, St Paul, Minn). Each type of ring is designed with specific physical and structural characteristics.

Recent studies show that 10% or more of patients who undergo mitral valve repair may require late reoperation for recurrent valve dysfunction,[10] which emphasizes the importance of optimizing repair durability. Previous clinical evidence suggests that a flexible ring is better in preserving mitral annular physiology.[11-16] A recent randomized animal experiment, however, demonstrated that both semirigid and flexible complete annuloplasty rings totally abolished physiologic mitral annular dynamics[17] and, furthermore, perturbed leaflet closing dynamics by tethering the posterior mitral valve leaflet in a semiopen configuration.[18]

The effects of different types of complete annuloplasty rings on annular and valvular physiology and long-term repair durability are unclear, but preservation of normal annular motion would intuitively be expected to be superior. Partial ring annuloplasty, as championed by Cosgrove and colleagues,[1,9,16] offers equivalent annular remodeling, resizing, and stabilizing properties, with potentially less perturbation of annular and leaflet function. We investigated alterations in annular and valvular function after partial ring annuloplasty and compared these changes with the effects of complete flexible ring annuloplasty in a sheep model.

Methods

In brief, 6 adult male sheep (77 ± 9 kg [mean ± standard deviation]) underwent mitral ring annuloplasty with a partial (posterior) flexible Tailor ring and placement of radiopaque markers in the left ventricle and around the mitral anulus. Five animals received a 29-mm Tailor ring and 1 received a 31-mm ring with 8 to 10 horizontal mattress stitches of 2-0 braided Dacron suture.

Surgical Preparation

Nine miniature radiopaque tantalum markers (inner diameter = 0.8 mm, outer diameter = 1.3 mm, length = 1.5-3.0 mm) were inserted into the left ventricle through a left thoracotomy. The mitral and aortic valves were assessed with epicardial echocardiography and Doppler color flow ultrasonography. Cardiopulmonary bypass was instituted using descending aortic and right atrial cannulation. Eight tantalum radiopaque markers were sutured approximately 45° from one another around the circumference of the mitral anulus through a left atriotomy. The mitral valve was sized by using both the distance between the fibrous trigones and the area of the anterior leaflet, and an appropriately sized Tailor ring was implanted with 8 to 10 interrupted horizontal mattress sutures. The animals were allowed to recover in the experimental animal cardiac surgical intensive care unit. Further details of our methods and animal procedures have been published previously, including implantation details in the Duran ring group.[17]

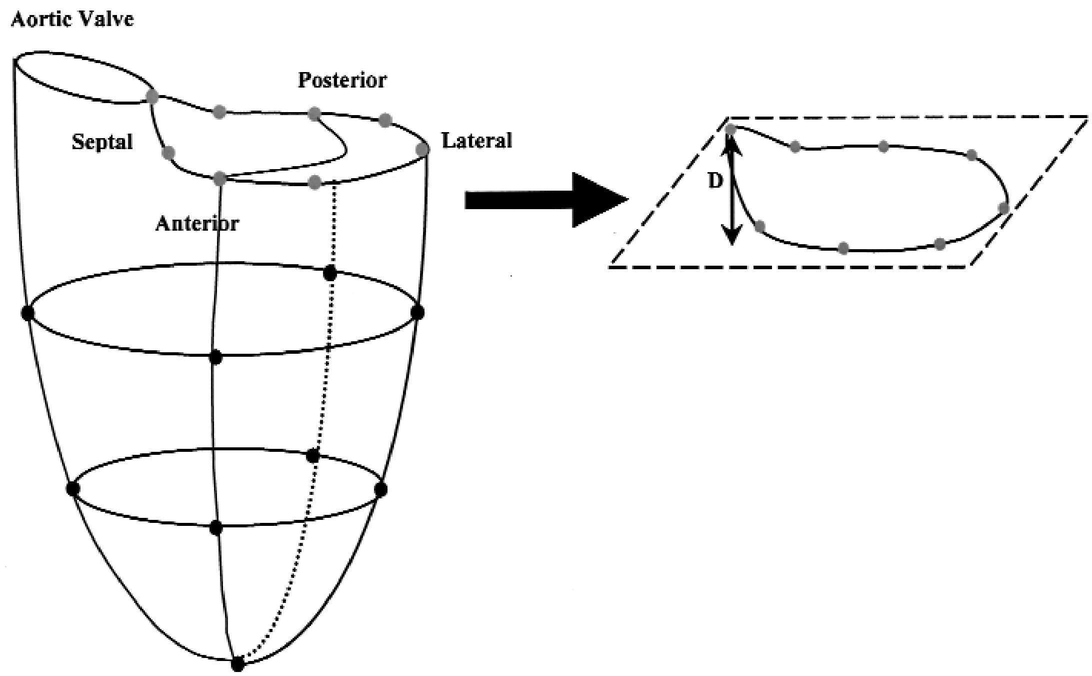

Figure 2. Anterior-posterior annular folding. A plane is fitted to the markers on the posterior anulus by using least-squares estimation. The distance *(D)* of marker *1* from that plane defines the anterior annular elevation and is used to quantify the amount of annular folding during the cardiac cycle.

Experimental Design

All animals received humane care in compliance with the "Principles of Laboratory Animal Care" formulated by the National Society for Medical Research and the "Guide for the Care and Use of Laboratory Animals" prepared by the Institute of Laboratory Animal Resources, National Research Council, and published by the National Academy Press, revised 1996. This study was approved by the Stanford Medical Center Laboratory Research Animal Review Committee and conducted according to Stanford University policy.

Data Acquisition

During myocardial marker studies performed 7 to 10 days after the operation, the animals were sedated with ketamine and diazepam, intubated, and mechanically ventilated (veterinary anesthesia ventilator 2000, Hallowell EMC, Pittsfield, Mass) with 100% oxygen. A Philips Optimus 2000 biplane lateral ARC 2/poly DIAGNOST C2 system (Philips Medical Systems North America, Bothell, Wash) was used to record videofluoroscopic data at 60 Hz, with the image intensifiers in the 9-inch mode. Two-dimensional (2-D) images from each of the 2 radiographic views (45° right anterior oblique and 45° left anterior oblique) were digitized and then merged to yield 3-dimensional (3-D) x, y, and z coordinates for each marker every 16.7 ms (Figure 1).[19] Analog LV pressure and electrocardiographic voltage were digitized and recorded on each video image during data acquisition.

Data Analysis

End-systole was defined as the videofluoroscopic frame preceding maximum negative dP/dt (–dP/dtmax); end-diastole was defined as the videofluoroscopic frame containing the peak of the electrocardiographic R wave.

LV Systolic Function

An instantaneous estimate of LV volume was calculated every 16.7 ms from the epicardial LV markers by means of a multiple tetrahedral model reconstructed from the marker coordinates and corrected for LV convexity. Although epicardial LV volume calculated in this manner overestimates true chamber LV volume, the change in LV volume is an accurate measurement of the change in chamber volume.[20] Thus, stroke volume is accurately calculated from the change in epicardial LV volume, but ejection fraction (or stroke volume normalized to epicardial LV volume) is substantially underestimated.

Mitral Annular Geometry

Mitral annular area, perimeters, and dimensions were computed from the 3-D marker coordinates without assuming circular or planar geometry. The 8 annular markers, together with their computed geometric centroid, were used to partition the mitral anulus into 8 triangular pieces, each having the centroid as its apex, and 2 adjacent annular markers defining the base. Annular area was computed from the sum of the 8 triangular areas (Figure 1). The muscular (posterior) annular perimeter was computed from the sum of the 6 contiguous mitral annular segment lengths enclosed between markers 2 and 8. The fibrous (anterior) annular perimeter was computed from the sum of segment lengths enclosed between markers 1 and 2 and between markers 1 and 8. The mitral septal-lateral and commissure-commissure dimensions were computed

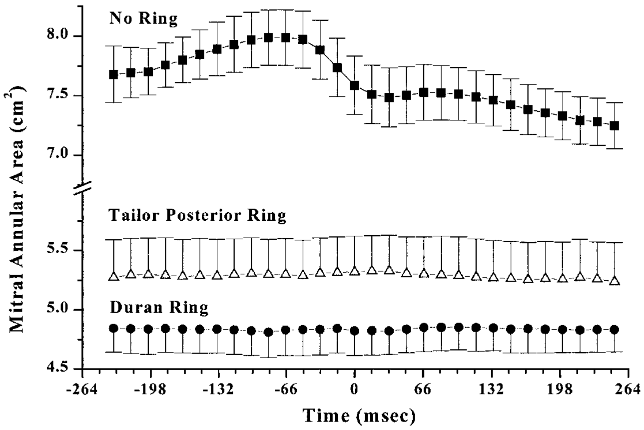

Figure 3. Mitral annular area versus time for animals with no ring, complete flexible Duran ring, and posterior flexible Tailor ring annuloplasty. Data are mean values for each group at each videofluoroscopic frame aligned at end-diastole. *Error bars* represent ±1 standard error of the mean.

from the distances in 3-D space between markers 1 and 5 and between markers 3 and 7, respectively.

The anterior anulus was defined as the annular segments corresponding to the fibrous perimeter, and the posterior anulus was defined as the segments corresponding to the muscular perimeter. Relative to the posterior anulus, the anterior anulus flexes toward the atrium. To quantify the amount of flexion or tilting during the cardiac cycle, a plane was fitted to the posterior annular markers by using least-squares estimation. Anterior annular elevation was defined as the vertical distance of marker 1 ("saddle-horn" marker) from that plane (Figure 2), whereas anterior-posterior mitral annular flexion was defined as the angle subtended by the saddle-horn marker and a plane fitted to the posterior annular markers. The angle was computed by taking the arcsine of the ratio of the perpendicular distance (elevation) of the saddle-horn marker from the posterior annular plane and the distance from the saddle-horn marker to the midpoint of the 2 commissure markers.

Statistical Analysis

All data are reported as means ± standard error of the mean unless specified otherwise. For each animal, data represent the mean of 3 consecutive cardiac cycles. Comparisons within and between groups were made with repeated-measures analysis of variance.

Results

The 3-D geometric changes of the mitral anulus after partial ring annuloplasty with a Tailor ring (Tailor; size 29 mm in 5 and 31 mm in 1) were compared with previously published results in a control group of sheep (no ring, n = 16) and sheep that underwent implantation of a Duran flexible ring annuloplasty (Duran; size 29 mm in 2 and 31 mm in 5).[17] All 3 groups underwent identical operations, marker placement, and postoperative care. Data were acquired in the no-ring group at 7 ± 1 days after the operation and in the Duran group at 8 ± 1 days. Differences in body weight were not significant among the 3 groups (control, 72 ± 9 kg; Duran, 69 ± 8 kg; and Tailor, 77 ± 9 kg). Necropsy confirmed that all annuloplasty rings were seated properly. MR was not present, as determined with transthoracic color Doppler echocardiography, in any animal at the time of data acquisition.

Hemodynamics

Differences in heart rate, end-systolic pressure, end-diastolic pressure, end-systolic volume, and stroke volume were not significant across the 3 groups (Table 1). Load-dependent (ejection fraction and peak +dP/dtmax , Table 1) indices of systolic function were also not statistically different among the 3 groups.

Mitral Annular Size and Shape

We have previously reported changes in the size and shape of the mitral anulus in the Duran group.[17] Figure 3 shows mitral annular area versus time for all 3 groups. In the no-ring group mitral area changed dynamically from a late diastolic maximum of 8.0 ± 0.2 cm^2 to an early systolic minimum of 7.2 ± 0.2 cm^2 ($P < .001$), whereas in the Duran group, as reported before, the area remained fixed at 4.8 ± 0.1 cm^2. Similar to that seen with the complete Duran ring, mitral annular area in the Tailor partial ring group remained fixed at 5.3 ± 0.3 cm^2 (Table 2).

Changes in the commissure-commissure and septal-lateral annular dimensions paralleled the changes in annular shape in the 3 groups (Figure 4). In the no-ring group the commissure-commissure dimension reached a late diastolic maximum length of 38.2 ± 0.8 mm and an end-systolic minimum length of 36.4 ± 0.8 mm ($P < .001$). The septal-lateral dimension demonstrated a late diastolic maximum length of 27.7 ± 0.4 mm and an end-systolic minimum length of 25.9 ± 0.4 mm ($P < .001$). In the Duran group the commissure-commissure and septal-lateral dimensions were static throughout the cardiac cycle (27.7 ± 0.7 mm and 21.8 ± 0.7 mm, respectively). In the Tailor group the commissure-commissure dimension was also fixed (31.2 ± 1.7 mm), but the septal-lateral dimension length decreased slightly during systole from 22.3 ± 0.9 to 21.5 ± 1.1 mm ($P = .078$).

We also compared changes in posterior (muscular) mitral annular perimeter and anterior (fibrous) perimeter in all 3 groups (Figure 4). The anterior perimeter in the Tailor group corresponds to the annular segment between the 2 ends of the partial (posterior) Tailor ring (markers *8* and *2*, Figure 1). The length changes in the posterior annular perimeter of the no-ring group during the cardiac cycle paralleled the changes in annular area. The posterior perimeter reached a late diastolic maximum of 8.1 ± 0.1 cm and an end-systolic minimum of 7.6 ± 0.1 cm ($P < .001$). The anterior perimeter in the no-ring group did not change during the cardiac cycle (26.5 ± 0.7 mm, $P = .017$). In contrast, both the posterior and

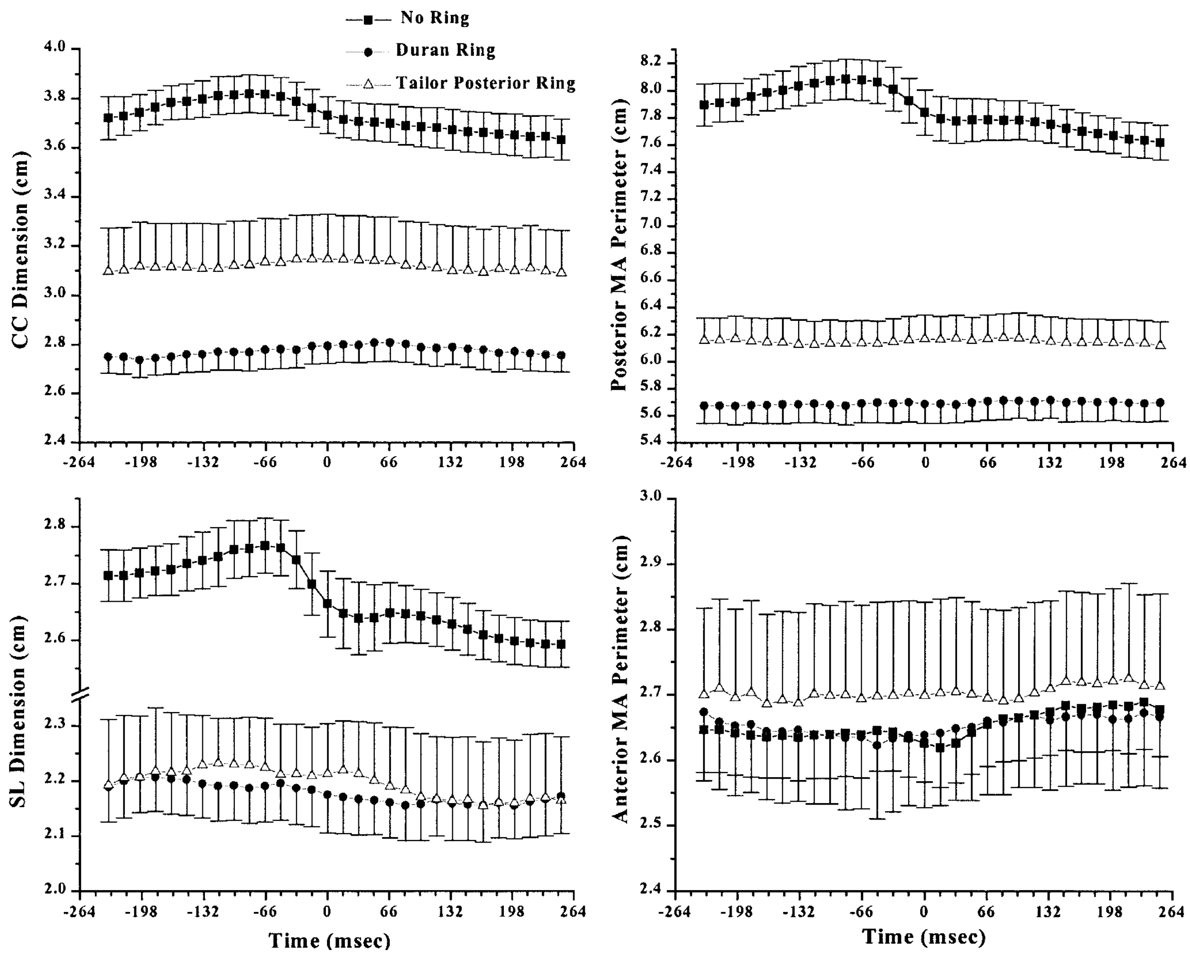

Figure 4. Mitral annular perimeters and dimensions for animals with no ring, complete flexible Duran ring, and posterior flexible Tailor ring annuloplasty. Data are mean values for each group at each videofluoroscopic frame and were aligned at end-diastole. Error bars represent ±1 standard error of the mean. *CC*, Commissure-commissure dimension; *SL*, septal-lateral dimension; *MA*, mitral annular.

anterior annular perimeters remained fixed in the Duran (5.7 ± 0.1 cm and 26.5 ± 1.0 mm, respectively) and the Tailor groups (6.2 ± 0.2 cm and 27.0 ± 1.4 mm, respectively).

During systole, the anulus folded (or flexed or tilted) in the septal-lateral dimension, as demonstrated by displacement of the anterior anulus away from the least-squares annular plane fitted to the posterior anulus toward the atrium during systole. Differences in annular folding among the 3 groups were assessed by computing elevation of the anterior annular marker from the least-squares plane (Figure 5). Both the no-ring and the Tailor ring groups showed similar changes in annular elevation during systole, going from a minimum near end-diastole of 6.7 ± 0.2 mm and 7.9 ± 0.2 mm, respectively, to a maximum at end-systole of 8.3 ± 0.2 mm ($P < .001$) and 9.1 ± 0.2 mm ($P = .014$), respectively. Anterior annular elevation in the Duran group was not as prominent, rising from 7.3 ± 0.3 to 8.2 ± 0.3 mm ($P = .069$). Similarly, anterior-posterior mitral annular flexion (shown as angular change in degrees, Figure 6) increased during systole in the control group and the Tailor group. In contrast, the flexion angle in the Duran group did not change significantly during the entire cardiac cycle.

Discussion

Although most surgeons agree that mitral annuloplasty constitutes an integral component of mitral valve repair, they continue to debate the choice of annuloplasty ring. Reproducible and predictable results are some of the advantages of ring annuloplasty over unconventional annular remodeling procedures, such as suture annuloplasty[21] or hand-crafted pericardial annuloplasty.[22] Ring annuloplasty is used to reshape and resize the mitral anulus to its presumed physiologic dimensions and additionally provides annular stabilization. Early and late failure of valve repair may be

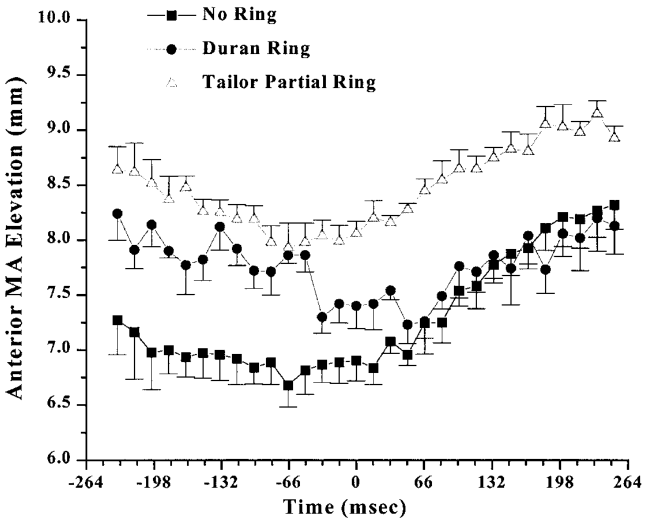

Figure 5. Elevation of the saddle-horn marker above a plane fitted to the posterior annular markers versus time for animals with no ring, a complete flexible Duran ring, and a posterior flexible Tailor ring annuloplasty. Data are mean values for each group at each videofluoroscopic frame and are centered around end-diastole (t = 0). *Error bars* represent ±1 standard error of the mean. Depicted is the anterior anulus height (or distance) from a plane fitted to the posterior annular markers by using least-squares estimation. *MA*, Mitral annular.

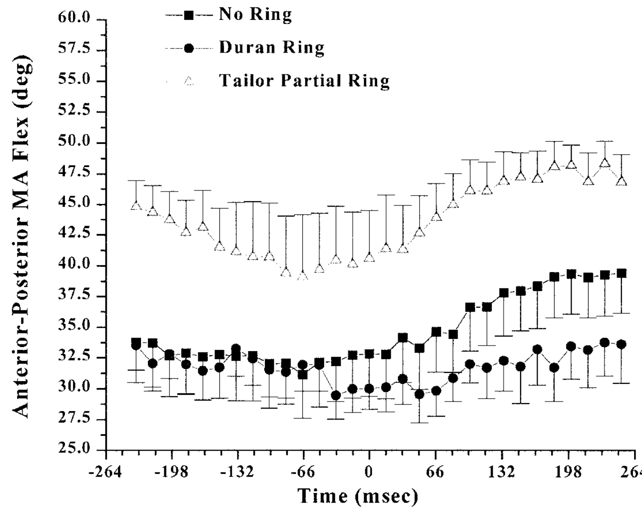

Figure 6. Mitral annular *(MA)* flexion expressed as the angle subtended by the saddle-horn marker and a plane fitted to the posterior annular markers throughout the cardiac cycle for animals with no ring, a complete flexible Duran ring, and a posterior flexible Tailor ring annuloplasty. Data are mean values for each group at each videofluoroscopic frame and are centered around end-diastole (*t* = 0). *Error bars* represent ±1 standard error of the mean.

attributed in part to nonphysiologic systolic closing stresses and stress distributions on the leaflets and perhaps to inadequate stabilization of the anulus. Proper annular remodeling with a ring appears to unload valvular stress onto the synthetic ring,[23] which should improve repair durability.

The controversy between semirigid and flexible annuloplasty rings originates from the perception that a flexible ring can remodel the mitral anulus while preserving its dynamic motion during the cardiac cycle.[11-16] The benefit of preserving annular dynamics is unclear, however, because studies have shown that either a flexible or rigid ring does not alter global or regional LV function.[24,25] Furthermore, the incidence of repair failure with either type of ring is similar,[3] suggesting that flexibility does not offer a demonstrable, clinically important durability advantage. Although clinical studies on the basis of 3-D echocardiography appear to show continued dynamic motion of the Duran flexible ring in vivo,[13-15] recent animal research shows that both types of rings fix the anulus,[17] which possibly explains the lack of objective functional clinical performance differences between the 2 rings. A third type of ring, the partial (or posterior) flexible annuloplasty ring, is purported to remodel and stabilize the posterior anulus between the fibrous trigones without interfering with the motion of the anulus. Introduction of partial annuloplasty rings, such as the Cosgrove-Edwards ring and subsequently the Tailor ring, offered renewed hope for preserving mitral annular dynamics after ring annuloplasty.

The experimental results in this study, however, surprisingly showed that a flexible partial Tailor ring also abolished mitral annular area and perimeter changes during the cardiac cycle. In the control group of animals, mitral annular area and perimeter underwent a rapid and large presystolic reduction, followed by a slower reduction during systole. In both the Duran and Tailor groups, mitral annular area and perimeter remained fixed throughout the cardiac cycle. The annular segment between the fibrous trigones is fibrous and relatively rigid during the cardiac cycle; because partial ring annuloplasty subtends the posterior anulus, perhaps it is not surprising that the effects of a partial Tailor ring on mitral annular area are similar to those of a complete Duran ring.

Both types of rings reduced mitral annular area, although the area reduction associated with the partial Tailor ring was significantly less than that seen with a complete Duran ring. Ring sizes were selected on the basis of the same size criteria. Even in normal ovine hearts without annular dilation, an appropriately sized annuloplasty ring reduces annular size by approximately 30%. The difference in area reduction between the 2 ring types can be explained by a difference in reduction of the commissure-commissure dimension. The complete Duran ring reduced the commissure-commissure dimension more than the partial Tailor ring, but both rings had similar effects on the mitral septal-lateral dimension. Thus, a Tailor ring preserved more of the elliptical annular shape than did the Duran ring.

Mitral annular size reduction with resultant fixation of the anulus may be necessary for long-term valve-repair durability by unloading suture line stresses and strains that would occur if the anulus continued to move in a normal dynamic fashion. Even surgeons who do not universally use a ring annuloplasty during valve repair still usually perform some type of posterior annular plication that probably fixes the anulus in a similar manner. On the basis of these and previous findings,[17] stabilizing the valve repair would appear to require some type of annular plication and fixation, which rejects the notion that preservation of annular dynamics is a major contribution to the short or long-term success of mitral repair.

The anulus is known to undergo flexion during the cardiac cycle. During systole, the anterior anulus tilts away from the LV outflow tract and toward the left atrium.[12,26] Preservation of this physiologic deformation could potentially be important in avoiding LV outflow tract obstruction after ring annuloplasty.[27] Both the complete Duran and partial Tailor rings allowed the anterior anulus to flex during systole, but only in the Tailor group was the degree of flexion similar to that in the control group. The Duran ring blunted some anterior annular flexion during systole. This difference between the ring and the control group was also observed in the behavior observed in septal-lateral dimension change. In the absence of changes in annular area and perimeter, changes in septal-lateral dimension reflect flexion of the anulus. The septal-lateral dimension decreased to a similar extent during systole in both the control and the Tailor groups, whereas in the Duran group the septal-lateral dimension remained constant.

These observations and previous findings in animals[17] challenge reports of clinical measurements of the mitral anulus using 3-D echocardiographic reconstruction in patients after ring annuloplasty, which claim a 10% to 26% annular area reduction with a Duran ring[12-15] and a 13% to 28% reduction with a Cosgrove-Edwards partial ring.[9,11,16] The discordance among the different human and experimental studies may arise from critical methodologic and analytic differences. The 3-D reconstruction of markers sutured to the mitral anulus yields precise definition of the coordinates of all annular markers at the same instant in the cardiac cycle.[28] Furthermore, the motion of each marker precisely tracks a unique anatomic locus on the mitral anulus, allowing accurate comparisons at different times in the cardiac cycle between derived geometric quantities, such as annular area, perimeter, or length. In contrast, 3-D echocardiographic reconstruction of the mitral anulus requires composing multiple 2-D slices acquired from different transducer orientations taken over dozens of cardiac cycles. Because of rotational and translational motions of the heart relative to the transducer, the part of the anulus visualized by an echocardiographic 2-D slice at different times during the cycle may not necessarily represent the same annular segment at all times. The tremendous disparity between reports measuring mitral annular area and dynamics in patients with a Cosgrove-Edwards ring using 3-D echocardiography clearly illustrates this point.[9,11] The measurement error introduced in the 3-D echocardiographic reconstruction by averaging data over several cycles and the error introduced by comparing reconstructions at different time points has probably not been adequately taken into account; such would require validation experiments with marker technology as the gold standard for comparison.

A second and possibly more important source of error in measuring mitral annular area and other annular measurements estimated from 3-D echocardiography occurs because short-axis planar projections of the anulus are used to compute those measurements. The 3-D reconstruction with marker data shows that the anulus is not planar, and furthermore, it undergoes folding during systole in the no-ring and Tailor ring groups. Thus, any 2-D projection of the anulus will interpret annular folding as a reduction in annular area, even if the true 3-D annular area does not change. In addition, during the cardiac cycle, the anulus tilts (or folds or flexes) relative to the long axis of the ventricle and its orthogonal 2-D short-axis projection plane. Such tilting will also change the projected annular size and area and further confound interpretation of the geometric measurements obtained from 2-D projected images.

This and previous experiments with marker technology have shown that either complete semirigid, flexible, or partial flexible ring annuloplasty rings abolish normal mitral annular dynamics and fix mitral annular area throughout the cardiac cycle in normal sheep. The current study, however, also revealed that a flexible partial ring preserves 3-D annular conformational changes, such as anterior annular flexion, during the cardiac cycle. The clinical effect on repair durability of preserving these subtle conformational changes is unknown. Preservation of normal mitral annular deformation, however, may influence the predisposition to LV outflow tract obstruction and possibly other complications after valve repair.

Study Limitations

Simultaneous biplane cinefluoroscopy and 3-D segmentation of the anulus between many miniature radiopaque markers allows accurate and reproducible determination of marker position, with a mean overall error of only 0.1 ± 0.6 mm every 16.7 ms.[29] Marker technology, however, requires suturing small markers to the area of interest, in this case the mitral anulus; the total weight of the markers and the effects of the small fixation sutures, however, should have a negligible effect on annular dynamics.

All data were collected with the animals in normal sinus rhythm. Doppler echocardiography confirmed that all ani-

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TABLE 2. Mitral annular dynamics

	No ring		Tailor ring		Duran ring	
	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
MAA (cm^2)	8.0 ± 0.2	7.2 ± 0.2*	5.3 ± 0.3	5.3 ± 0.3	4.8 ± 0.1	4.8 ± 0.1
SL (mm)	27.7 ± 0.4	25.9 ± 0.4*	22.3 ± 0.9	21.5 ± 1.1	21.8 ± 0.7	21.8 ± 0.7
CC (mm)	38.2 ± 0.8	36.4 ± 0.8*	31.2 ± 1.7	31.2 ± 1.7	27.7 ± 0.7	27.7 ± 0.7
P_{ANT} (mm)	26.5 ± 0.7	26.5 ± 0.7	27.0 ± 1.4	27.0 ± 1.4	26.5 ± 1.0	26.5 ± 1.0
P_{POST} (mm)	81.0 ± 1.0	76.0 ± 1.0	62.0 ± 2.0	62.0 ± 2.0	57.0 ± 1.0	57.0 ± 1.0
D (mm)	8.3 ± 0.2	6.7 ± 0.2*	9.1 ± 0.2*	7.9 ± 0.2*	8.2 ± 0.3	7.3 ± 0.3

Means ± standard error of the mean are reported for the maximum and minimum values averaged over 3 consecutive cardiac cycles for each animal. *MAA*, Mitral annular area; *SL*, mitral septal-lateral dimension; *CC*, mitral commissurecommissure dimension; P_{ANT}, anterior anulus length; P_{POST}, posterior anulus length; *D*, anterior annular elevation.
*Change between maximum and minimum values was significant by repeated-measures analysis of variance.

mals had competent mitral valves during data acquisition. Furthermore, hemodynamics and LV systolic function were similar among all 3 groups, indicating comparable LV loading conditions and LV function. The observed differences in mitral annular dynamics among the 3 groups, therefore, cannot be explained by differences in LV loading or systolic function, which are well appreciated to affect mitral annular dynamics.

The clinical applicability of these results is clearly limited because this is an animal experiment using normal hearts without preexisting valvular pathology and its consequent changes in LV size and function. Nonetheless, because annular dilation occurs predominantly along the posterior anulus, ring annuloplasty under those conditions would result in a relatively greater magnitude of annular area reduction.

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